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Angular correlation measurements on levels in Se^{76} and Fe^{56}

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With 5 figures in the text

ABSTRACT

The angular distributions of cascading gamma rays in Se^{76} and Fe^{56} have been investigated with an automatic directional correlation apparatus. The measured cascades in Se^{76} are (keV): 560–660, 560–1220, 560–2100, 1220–1220, 1220–1440, giving the following spins of energy levels in Se^{76}, keV (I, π): 560 (2 +), 1216 (2 +), 1788 (2 +), 2434 (3), 2556 (3 −). The first three levels may be of one, two and three phonon vibrational character respectively, and the 2656 keV level is of probable octupole vibrational type.

The cascades 0.85–3.26, 1.24–2.02 and 1.24–1.76 MeV in Fe^{56} give a 3 + spin to the 4.10 MeV level and a (5 +) spin level at 3.84 MeV. The spin assignment of the 4.10 MeV level is unique 3 +, but it is in discrepancy with the interpretations of earlier correlation measurements.

Levels in Se^{76}

The decay scheme of As^{76} (26 h) has been investigated by many authors [1]. It consists mainly of four levels at 0, 559, 1216 and 2656 keV having spins and parities 0 +, 2 +, 2 + and probably 3 respectively. Recently L. V. Gustova and O. V. Chubinskii [2], R. K. Girgis, R. A. Ricci and R. van Lieshout [3] and G. Bäckström and I. Marklund [4] have reinvestigated this decay scheme. Their results are in good agreement and establish new levels of energies 1788 keV, 2112 keV and 2434 keV. The decay scheme of As^{76} proposed by Bäckström and Marklund is presented in Fig. 1.

Directional correlation measurements have been made by T. Lindqvist and I. Marklund [5], C. F. Coleman [6] and E. G. Funk and M. L. Wiedenbeck [7]. The results obtained by these authors are collected in Table I. For the 660 keV–560 keV cascade the results of Lindqvist and Marklund and those of Coleman agree within the limits of errors. From these measurements the mixing parameter δ for the 660 keV transition is $\delta = -7.2 \pm 1.5$ and $\delta = -3.7 \pm 1.9$ respectively. The much smaller A_2 value obtained by Funk and Wiedenbeck for the 660 keV–560 keV correlation gives $\delta = +16$ for the 660 keV transition.

In the cases, when the 1440 keV–1220 keV correlation was measured by selection of the integral gamma ray spectra above 1150 keV, most of the coincidences must have involved also the 1220 keV–1220 keV cascade. This fact can explain the low values reported for the correlation coefficients of the 1440 keV–1220 keV cascade.

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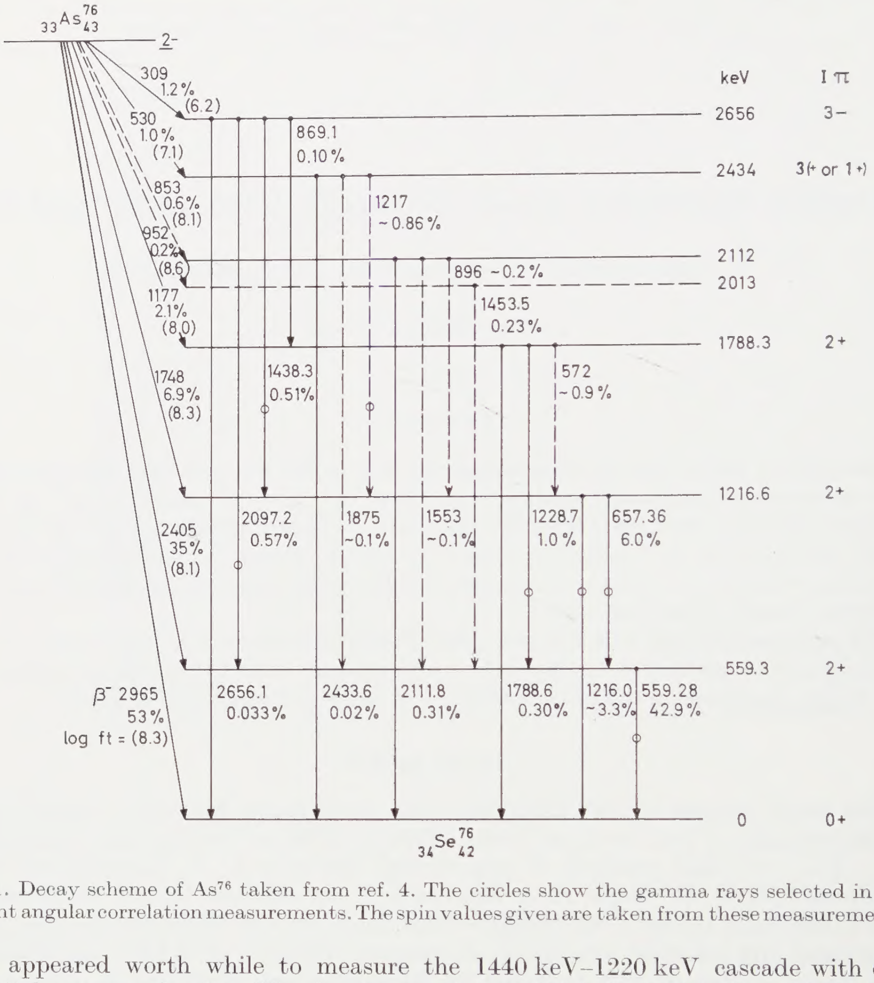

Fig. 1. Decay scheme of As^{76} taken from ref. 4. The circles show the gamma rays selected in the present angular correlation measurements. The spin values given are taken from these measurements.

It appeared worth while to measure the 1440 keV–1220 keV cascade with differential energy selection. We also measured the 1220 keV–1220 keV and 1220 keV –560 keV cascades to establish the spins of the new levels at energies 2434 keV and

TABLE I

Cascade	T. Lindqvist and I. Marklund		C. F. Coleman		E. G. Funk and M. L. Wiedenbeck	
	A_2	A_4	A_2	A_4	A_2	A_4
650– 550 keV	−(0.169 ± 0.015)	+(0.293 ± 0.030)	−(0.209 ± 0.031)	+(0.246 ± 0.045)	−(0.042 ± 0.015)	+(0.319 ± 0.023)
1400–1200 keV			−(0.091 ± 0.024)	+(0.057 ± 0.034)	−(0.076 ± 0.022)	−(0.003 ± 0.032)
2050– 550 keV					−(0.027 ± 0.022)	−(0.075 ± 0.033)

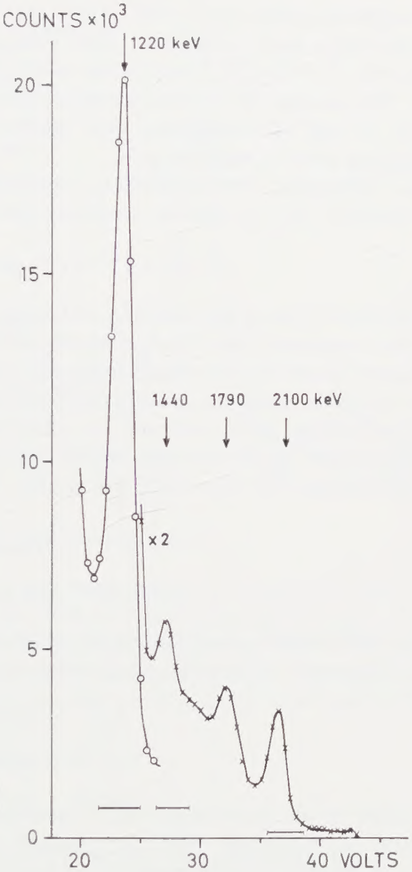

Fig. 2. High energy scintillation spectrum of As^{76}. Analyzer settings are indicated in the figure.

1788 keV respectively. For the 2656 keV level Funk and Wiedenbeck give preference for spin 3 because of the absence of cross-over transition from this level. All new measurements, however, point out the existence of such a transition. The 2100 keV –560 keV cascade was remeasured to confirm the spin value of the 2656 keV level and the measurement of the 660 keV–560 keV correlation was repeated.

As source material spectroscopically pure As metalic powder was used. After neutron irradiation in the Stockholm reactor the As-powder was dissolved in dilute HCl. The short life-times of the 559 keV and 1216 keV excited states and the liquid form of the source excluded observable attenuation due to extranuclear fields.

In Fig. 2 the high energy part of the scintillation gamma ray spectrum of As^{76} is presented. The analyzer settings are indicated.

Experimental procedure

The angular correlation measurements were made with an automatic coincidence spectrometer described elsewhere [8]. Two $1\frac{1}{2}$ in. × $1\frac{1}{2}$ in. NaI crystals were used, and the angle between the fixed and movable detector was changed every fifteen minutes in the cycle 225°, 180°, 135°, 90°, 90°, 135°, 180° and 225° until sufficiently good statistics were obtained. The channel settings and the time resolution of the instrument, $2\tau = 3 \times 10^{-8}$ sec., were carefully checked during the periods of measurements. The source to crystal distance was 50 mm. The counters were shielded frontally by 5 mm of aluminium and lateral lead shielding was employed to eliminate coincidences due to scattering.

After correction for accidental coincidences and coincident contribution from other cascades the A_2 and A_4 coefficients in the correlation function

$$W(\theta) = 1 + A_2 P_2 (\cos\theta) + \mathrm{A}_4 P_4 (\cos\theta)$$

were calculated using the method of Gimmi *et al.* [12]. The coefficients thus obtained were then corrected for the counters solid angles using an earlier, experimentally determined curve for the same geometry [8]. For the interpretation of the A_2 and A_4 values we have used the graphs representing A_2 and A_4 vs. δ which are given in ref. [13]. The sources were enclosed in cylindrical lucite holders 2 mm in diameter and 7 mm in length. Such a source container was filled to one half of its volume. Under these conditions no correction for source dimensions was necessary.

Results

660 keV–560 keV correlation

Both differential discriminators selected both the 660 keV and 560 keV photopeaks. The result after solid angle correction is:

$$A_2 = -(0.195 \pm 0.007)$$
$$A_4 = +(0.304 \pm 0.017).$$

This value is in agreement with previous measurements by Lindqvist and Marklund and by Coleman. The very small A_2 value obtained by Funk and Wiedenbeck is difficult to understand. It is not very probable that the result can be attenuated by the fact that the 560 keV photopeak is composed because of the very low intensity of the additional components. Our result is in agreement with spin 2 for the 1216 keV level and gives $6 \leqslant \delta \leqslant 7$ ($\delta < 0$) for the 660 keV transition. If one defines $Q = \delta^2/(1 + \delta^2)$—the quadrupole content, the data are consistent with Q equal to 0.977 ± 0.003. That gives for the 660 keV gamma ray a mixture of 97.7 ± 0.3 % electric quadrupole and 2.3 ± 0.3 % magnetic dipole radiation.

2100 keV–560 keV correlation

The experimental coefficients corrected for finite geometry are:

$$A_2 = -(0.020 \pm 0.011)$$
$$A_4 = -(0.003 \pm 0.010).$$

This result is only in agreement with a spin 3 assignment for the 2656 keV level ($0.05 \leqslant \delta \leqslant 0.07$; $\delta < 0$). The small log *ft* value of the beta branch feeding this level suggests minus parity. If this is the case the small δ value indicates that the 2100 keV transition has almost pure $E1$ character.

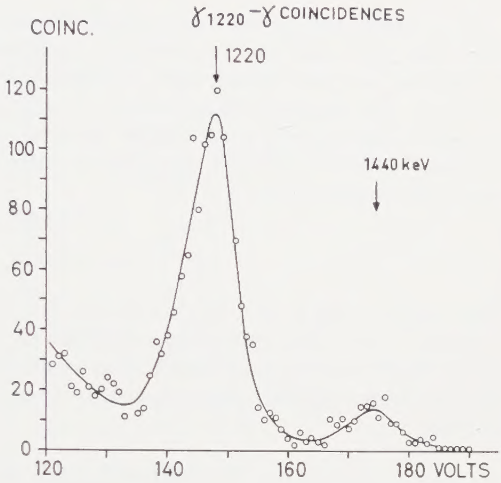

Fig. 3. The 1220 keV coincidence spectrum with the 1440 keV and 1220 keV gamma lines.

1220 keV–1220 keV correlation

In this case both differential discriminators were set at the 1220 keV photopeaks. The 1220 keV coincidence spectrum with the 1440 keV and 1220 keV lines is presented in Fig. 3. On the basis of this figure the conbribution from the 1440 keV–1220 keV cascade was estimated to be 17 %. The correlation coefficients, corrected for the finite solid angle of the counters and the contribution from the 1440 keV–1220 keV cascade, are:

$$A_2 = -(0.040 \pm 0.012)$$

$$A_4 = +(0.008 \pm 0.030).$$

This angular correlation result is in agreement with the spin assignments:

Spin of 2434 keV level	Mixing parameter for upper 1220 keV gamma ray
1	$\delta \approx 0.17$
3	$-0.06 \leqslant \delta \leqslant -0.02$
4	$\delta \approx 0.2;\ -3.1 \leqslant \delta \leqslant -2.7$

The possibility of spin 4 can be excluded on the basis of the observed cross-over transition from the 2434 level. From the angular correlation measurement it is not possible to distinguish between the 1 and 3 spin possibilities for this level. However, the intensity ratio of the cross-over transitions from the 2656 keV and 2434 keV levels strongly supports a spin 3 assignment for the latter one.

1220 keV–560 keV correlation

The differential discriminators were set at the 560 keV and 1220 keV photopeaks respectively. With such channel settings the 1217 keV–(657 keV)–560 keV correlation gives a 36 % coincidence contribution to the measurements, assuming the gamma intensities given in the decay scheme.

If we make use of the information about the 1217 keV gamma ray obtained from the 1220 keV–1220 keV correlation measurement and assume that the 657 keV transition has pure quadrupole character (experimentally 97,7 % $E2$) it is easy to compute the angular distribution of this one-third 1217 keV–(657 keV)–560 keV cascade. This angular distribution function is explicitly given in ref. [8]. Our result for the 1220 keV–560 keV correlation after correction for the contribution from the one-third cascade is:

$$A_2 = 0.206 \pm 0.015$$

$$A_4 = 0.024 \pm 0.030.$$

This result gives 2 ($4 \times 10^{-2} \leqslant \delta \leqslant 8 \times 10^{-2}$; $\delta < 0$) as the only possible spin for the 1788 keV level. The 3 and 4 possibilities are just outside our limits of error. Because of the large correction applied to this measurement they might be taken into account, but the strong ground state transition from the 1788 keV level excludes these possibilities.

1440 keV–1220 keV correlation

The differential settings of the channels are pointed out in Fig. 2. In this case no coincident background was present. The result is:

$$A_2 = -(0.178 \pm 0.029)$$

$$A_4 = +(0.027 \pm 0.066).$$

This result is in agreement with the spins given in the table below:

Spin of 2656 keV level	Mixing parameter for the 1440 keV gamma ray
1	$0.04 \leqslant \delta \leqslant 0.09$
3	$0.10 \leqslant \delta \leqslant 0.18$
4	$0.38 \leqslant \delta \leqslant 0.48$

Again the cross-over transition from the 2656 keV level excludes the spin 4 possibility. Combining this data with the unique result obtained from the 2100 keV–560 keV cascade, we assign a spin-parity 3 − for the 2656 keV level. The 1440 keV gamma ray has almost pure $E1$ character.

The present results are included in the decay scheme (Fig. 1) and are discussed in the preceding paper [4].

Levels in Fe^{56}

The decay scheme of Co^{56} has been recently reinvestigated by P. Kienle and R. E. Segel [9]. The proposed decay scheme is presented in Fig. 4. The 4.10 MeV level decays through the 2.02 MeV and 3.26 MeV gamma rays to the levels at 2.08 MeV and 0.85 MeV. The 3.84 MeV level decays mainly through the 1.76 MeV transition to the 2.08 MeV level. In the decay scheme given by Kienle and Segel the 4.10 MeV and 3.84 MeV levels have spin assignments 4 + and (3 +) respectively.

The angular correlation measurements from which the spins of the 4.10 MeV and 3.84 MeV levels can be derived were made by M. Sakai [10] and by Poppema, Siekman, Van Wageningen and Tolhoek [11]. This last group used alligned Co^{56}

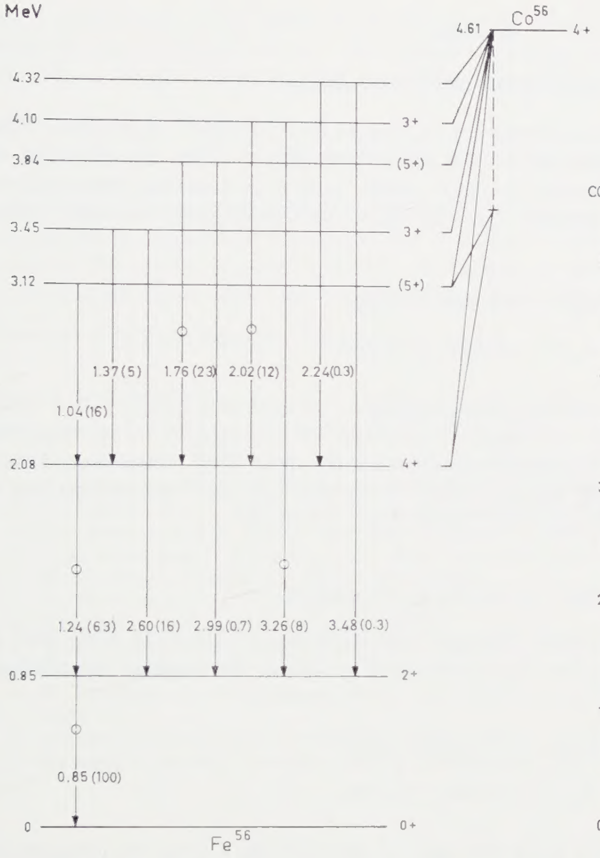

Fig. 4.

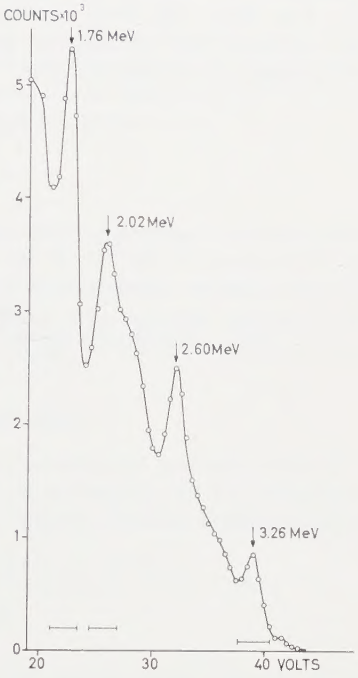

Fig. 5.

Fig. 4. Decay scheme of Co^{56} taken from ref. 9. The circles indicate the gamma rays selected in the present angular correlation measurements.

Fig. 5. Scintillation spectrum of Co^{56} in the high energy region. The lines below the curve indicate the analyzer settings.

nuclei. The measurements of Sakai as well as the measurements of Poppema *et al.* are in agreement with both 5 and 3 spin possibilities for the 3.84 MeV level. For the 4.10 MeV level the measurement of Poppema *et al.* gives spin 4 + as a unique answer (the remaining spin 2 possibility can be easily excluded). The accuracy of the measurement by Sakai for the 2.02 MeV–1.24 MeV correlation does not allow any conclusion with certainty, but is in agreement with a 4 (Q) 4 (Q) 2 sequence for this cascade.

We have remeasured three cascades: 3.26 MeV–0.85 MeV, 2.02 MeV–1.24 MeV and 1.76 MeV–1.24 MeV in order to check the spin assignments for the 4.10 MeV and 3.84 MeV levels. In Fig. 5 the single scintillation spectrum is presented. The channel settings used in the directional correlation experiments are indicated. Co^{56} was produced by the reaction Fe^{56} $(p,n)Co^{56}$ using 20 MeV protons in the Oak Ridge cyclotron. Cobalt was then separated from iron by ion exchange.

Results

3.26 MeV–0.85 MeV correlation

The first differential discriminator was set to accept the 0.85 MeV photopeak. The setting of the second discriminator can be seen from Fig. 5. The contribution of the 3.48 MeV–0.85 MeV correlation is very small, and it is assumed that it does not influence the correlation pattern for the 3.26 MeV–0.85 MeV cascade. After solid angle corrections we get:

$$A_2 = +(0.092 \pm 0.012)$$
$$A_4 = -(0.028 \pm 0.025).$$

This result is in agreement with spin 4 ($1.5 \leqslant \delta \leqslant 1.7$; $\delta < 0$) and spin 3 ($0.20 \leqslant \delta \leqslant 0.25$; $\delta < 0$) for the 4.10 MeV level. The 4 assignment (comparatively large δ value) requires rather extensive admixture of octupole radiation for the 3.26 MeV transition. If we alternatively assume spin 3 for the 4.10 MeV level, the 3.26 MeV transition has a more common mixture of (95.2 ± 1.1) % D and (4.8 ± 1.1) % Q.

2.02 MeV–1.24 MeV correlation

In this case the background from Compton contribution of the 2.24 MeV line is negligible (see the intensities in the decay scheme Fig. 4). As the angular correlation measurement result we obtain:

$$A_2 = -(0.048 \pm 0.012)$$
$$A_4 = -(0.010 \pm 0.028).$$

If we exclude values higher than 4 for the spin of the 4.10 MeV level on grounds of the observed reasonable intensity of the 3.26 MeV transition, this result is in unique agreement with spin 3 for this level. The δ value ($0.09 \leqslant \delta \leqslant 0.13$; $\delta > 0$) gives about 1 % quadrupole admixture for the 2.02 MeV gamma ray.

1.76 MeV–1.24 MeV correlation

The experimental result was in this case corrected for 31 % contribution of coincident Compton background from the 2.02 MeV gamma line giving:

$$\mathrm{A}_2 = -(0.101 \pm 0.010)$$
$$A_4 = -(0.013 \pm 0.021).$$

This result gives spin 5 ($0.02 \leqslant \delta \leqslant 0.06$; $\delta > 0$) and 3 ($0.03 \leqslant \delta \leqslant 0.07$; $\delta > 0$) as possibilities for the 3.84 MeV level. The intensity ratio between the 2.99 MeV and 1.76 MeV gamma rays rather strengthens the former possibility.

The present results are included in the decay scheme Fig. 4. The first angular correlation measurement gave preference for a spin 3 assignment of the 4.10 MeV level, and when another cascade was investigated this measurement gave a unique spin 3 assignment. This result is in discrepancy with earlier tentative spin 4 assignments for the 4.10 MeV level. The positive parities of the 4.10 MeV and 4.84 MeV levels are concluded from the log *ft* values 6.1 and 6.4 respectively.

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